Bucholz et al., Journal of Petrology, 2018 – APPENDIX

Detailed description of geology and petrogenesis of studied localities

ARCHEAN LOCALITIES

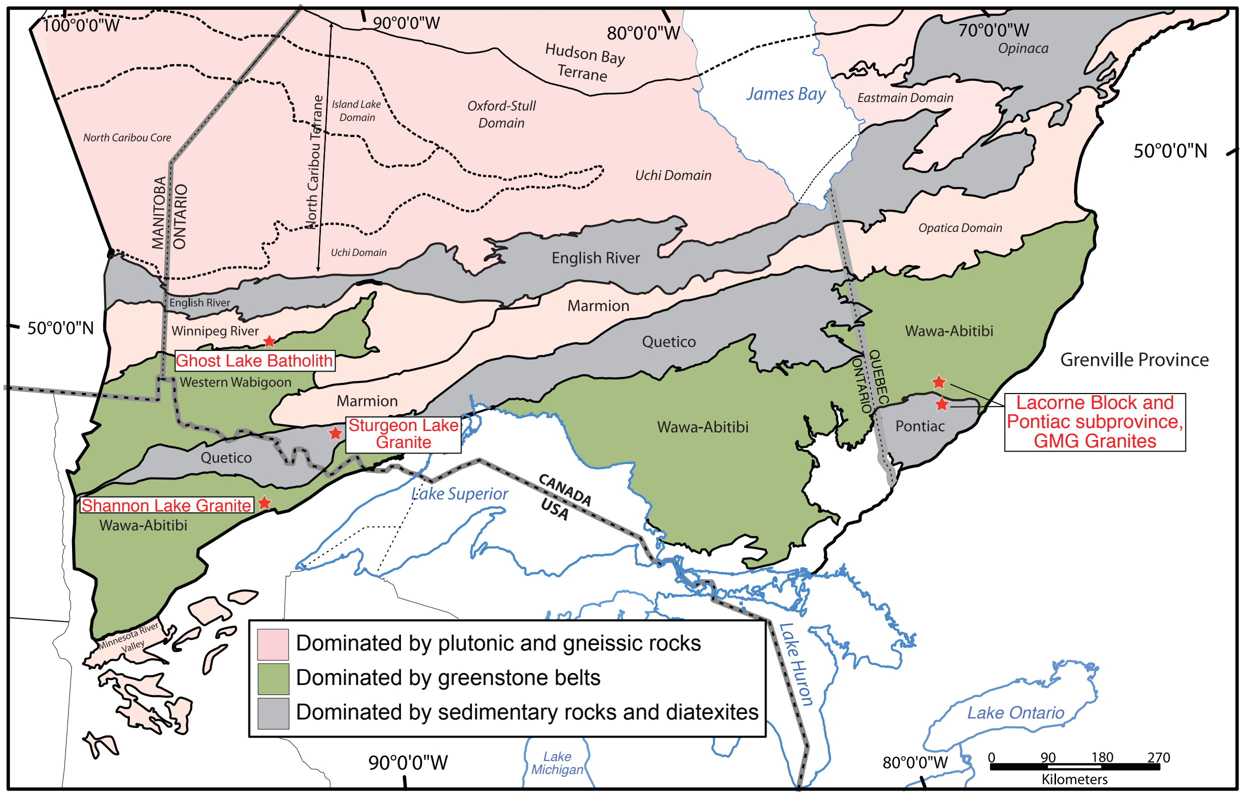

Figure A1: Terranes and domains of Superior Province in Canada (Ontario and Quebec) and United States (Minnesota) after Stott et al. 2010. Terranes/domains are colored by the lithologies they are dominated by, although in detail each terrane are heterogeneous mixtures of multiple rock types. Localities considered in this study are marked with red stars.

Ghost Lake batholith, Ontario (2685 Ma)

The Ghost Lake batholith (GLB) is situated at the Winnipeg River-Wabigoon subprovince boundary, which was defined as the Sioux Lookout terrane by Beakhouse, 1988 & 1999 (Fig. A1). The Sioux Lookout terrane is composed of (a) thrusted metasedimentary (Zealand/Minnitaki/Warclub Units) and metavolcanic assemblages that have a depositional age between 2733±1 and 2706±2 Ma (Blackburn *et al.*, 1991; Davis, 1990; Davis *et al.*, 1988) and (b) a 150-km-long belt of peraluminous granite plutons, including the GLB, which is the largest, and associated with pegmatites that contain economic-grade quantities of Li, Rb, Cs, Be, Nb, Ta, and Ga (Breaks and Moore, 1992). The Zealand Unit is characterized by three ductile deformation events (D_1, D_2, & D_3), E-striking foliations, a wide range in metamorphic grades (chlorite to sillimanite-kspar), and zones of incipient migmatization (Blackburn et al., 1991; 1982; Breaks, 1991; Breaks and Moore, 1992). The metamorphic gradient in the Dryden township area just south of the GLB increases steeply northward (50ºC/km) from the low-grade Wabigoon subprovince towards the GLB. Mineral assemblages (Bartlett, 1978; Thurston and Breaks, 1978) and thermobarometry (Campion *et al.*, 1986) on metapelites from the southern margin of the Sioux Lookout terrane yield metamorphic conditions of 550-750ºC and ~0.4 GPa, which is typical of the low pressure-high temperature regional metamorphism of the NW Superior province (Ayres, 1978; Thurston and Breaks, 1978). On the W and NW margins of the batholith, clastic sediments that have been metamorphosed sufficiently to have formed migmatites are present. In contrast, host rocks to the E and S contain mineral assemblages characteristic of the sillimanite-muscovite zone, but do not preserve evidence for incipient melting.

The GLB consists of eight internal units comprising a volumetrically-dominant, biotite(±cordierite) granite (units GLB-1 and -2 of Breaks and Moore, 1992), lesser amounts of locally garnet-bearing biotite+muscovite granite (GLB-3, Fig. A2A), and highly evolved, tourmaline+garnet+muscovite-bearing pegmatitic granitic facies (GLB-4 to -8) found primarily in the eastern lobe of the GLB that locally contains beryl and/or cassiterite. Samples from units GLB-1 and GLB-3 were selected for this study. The western part of the Ghost Lake Batholith is weakly foliated and contains enclaves of metagrewacke and metapelite. To the east, the intensity of foliation and abundance of the enclaves decrease to the point that the most eastern lobe of the batholith is either massive or preserves original magmatic layering. However, locally on the E margin of the batholith, there are zones rich in partially melted, sedimentary enclaves (Fig. A2B). Cross-cutting relationships between the GLB and deformation structures in the Zealand metasediments indicate that the chemically least evolved part of the GLB intruded between the D_1 and D_2 deformational events (Breaks and Moore, 1992). On the eastern margin of the GLB, granitic pegmatites are hosted in, though not locally derived from, mafic metavolcanic rocks (e.g., Mavis Lake Pegmatite).

A detailed examination of the petrology and chemistry of the GLB was presented by Breaks and Moore (1992), who proposed the following petrogenetic model for the GLB. Wackes and mudstones (now comprising the Zealand-Minnitaki-Warclub metasediments) were deposited as turbidites in basins and subsequently buried and partially melted during collision (between 2710-2698 Ma, (Beakhouse and McNutt, 1991; Corfu, 1988; Davis *et al.*, 1988)) of an arc (the Wabigoon subprovince, (Blackburn *et al.*, 1991) with an older, 3 Ga microcontinent (Winnipeg River subprovince). Burial of the sediments under high-T, low-P conditions resulted in anatexis and production of widespread production of peraluminous granitic melts (c. 2685 Ma, Davis et al 1990). Subsequent cooling and in-situ crystallization resulted in the accumulation and extraction of late-stage liquids that formed the small volumes of pegmatites.

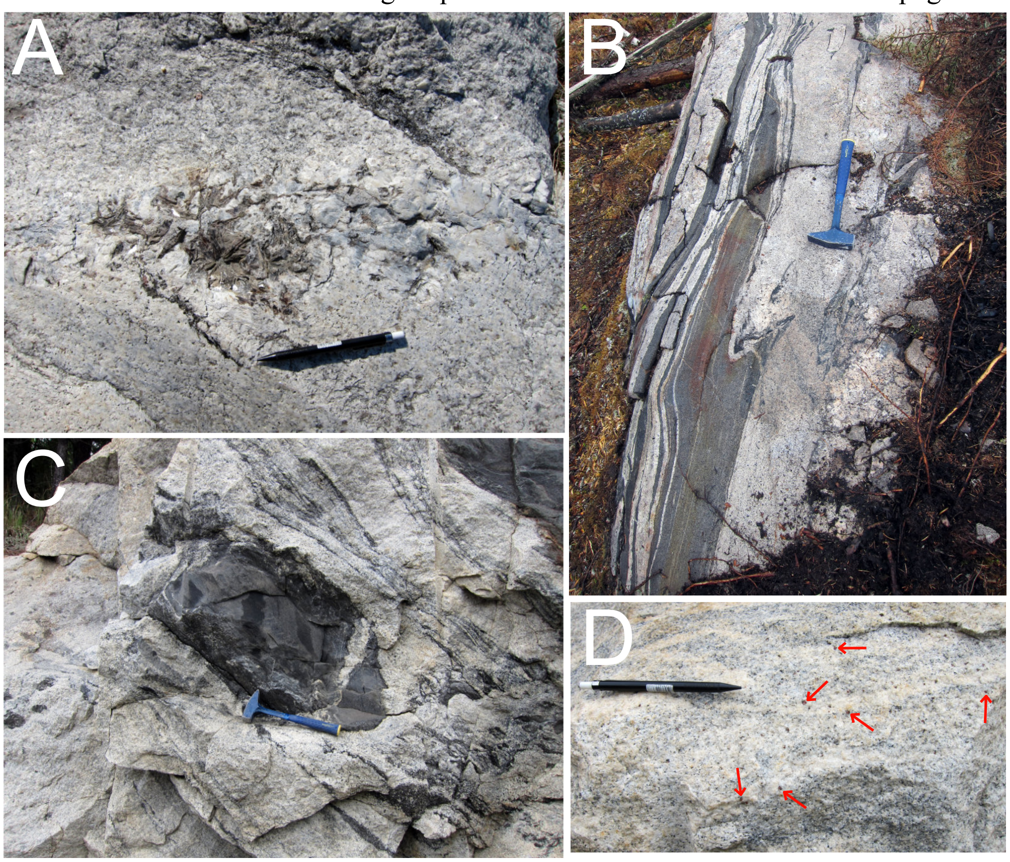

Figure A2: Field photographs. Hammer is 36 cm long. Mechanical pencil is 13.5 cm in length. A) Pegmatitic pod with muscovite rosettes hosted within biotite+muscovite granite in the Ghost Lake Batholith (location of photo: N49º48'53.7", W 092º57'4.7"). B) Metasediment-rich zone of Ghost Lake Batholith (location of photo: N 49º50'54.5", W 092º41'37.4"). C) Metasedimentary xenolith in garnet-bearing muscovite+biotite Sturgeon Lake granite. Block is infiltrated by granitic veins and has diffuse margins with granite, demonstrating evidence for partial digestion and incorporation into granite. Stretched mafic sedimentary schlieren are common. (location of photo: N 48º40'48.2", W 090º53'14.9") D) Typical appearance of biotite+muscovite+garnet leucogranite of the Sturgeon Lake granite. mm- to cm-scale garnets indicated with red arrows.

Sturgeon Lake granite, Quetico subprovince, Ontario

The Sturgeon Lake granite is part of the ~1200 km-long Quetico subprovince (Fig. A1), which comprises predominantly monotonous metagraywacke and locally-derived migmatites and granites (Percival and Williams, 1989). The graywackes were likely rapidly deposited as turbidites into a deep basin with a mixed volcanic-plutonic source region (Devaney and Williams, 1989). Tectonic models for the Quetico subprovince suggest a forearc depositional setting (Card, 1990; Fralick *et al.*, 2006; Langford and Morin, 1976; Percival and Williams, 1989). The sedimentary succession is steeply dipping, multiply deformed, and variably metamorphosed. Metamorphism increases towards the central axis of the subprovince, with greenschist facies near the northern and southern margins and granulite facies rocks with migmatites in the center (Pirie and Mackasey, 1978; Sawyer, 1983; Williams, 1987). Depositional age constraints based on detrital zircon ages suggest slightly older ages for the northern Quetico sediments (2696-2698 Ma; (Davis *et al.*, 1990)) than the south (<2692 Ma, (Zaleski *et al.*, 1999)).

Parts of the central Quetico subprovince consist of peraluminous leucogranites interlayered with biotite schist on the scale of decimeters to tens of meters, forming a regional migmatite unit that has been mapped as "schist-rich migmatite" (Southwick, 1972; Southwick and Ojakangas, 1979; Southwick and Sims, 1980). Locally, the peraluminous leucogranites form discrete bodies of segregated granite, such as the Sturgeon Lake granite (Percival and Williams, 1989; Southwick, 1991). The Sturgeon Lake granite is a muscovite-bearing leucogranite with biotite and/or garnet (Fig. A2D) and/or sillimanite. Dikes of granitic pegmatite with similar mineralogy are present in the biotite-schist host rock, and inclusions of this biotite-schist are common in the granite (Fig. A2C). The peraluminous granites are likely derived through biotite-dehydration melting of the aluminous metasediments that characterized the Quetico subprovince at mid-crustal depths (Day and Weiblen, 1986; Sawyer and Barnes, 1988; Southwick, 1991). Monazite U-Pb ages and cross-cutting relationships with other Archean granites suggest that the Sturgeon Lake granite crystallized at ~2671 Ma (Percival and Sullivan, 1988; Southwick, 1991).

Shannon Lake granite, Wawa subprovince, Minnesota

The Shannon Lake granite is part of the Giants Range batholith, which is a composite granitoid body that intrudes deformed supracrustal rocks in the western Wawa subprovince of Minnesota (Fig. A1) (Boerboom and Zartman, 1993). The host rocks are composed of complexly deformed metasedimentary and metavolcanic rocks that have undergone two major periods of deformation: a D_1 thrusting event which produced large-scale, locally recumbent folds and a D_2 event producing NE-striking, upright folds and steep, axial-planar cleavage (Jirsa *et al.*, 1991). Peak metamorphic conditions vary from greenschist to amphibolite facies and they likely occurred during D_2. The Britt granodiorite, a hornblende-bearing granodiorite to monzodiorite that intruded early in the history of the Giant Range batholith, was deformed and metamorphosed during D_2. In contrast, the Shannon Lake granite was emplaced during or after D_2 and is undeformed. All the rocks of the Giant Range batholith are cut by ~2120 Ma diabase dikes (Beck, 1988).

The Shannon Lake granite is exposed over a wide area (10 km x 35 km) and is composed predominantly of a weakly foliated muscovite-biotite granite (with accessory garnet, tourmaline, and beryl) with local centimeter- to decimeter-scale pegmatite dikes containing K-feldspar+muscovite+quartz±tourmaline. Dikes of the Shannon Lake granite intrude the Britt granodiorite and D_2-deformed supracrustal rocks (Boerboom and Zartman, 1993). In addition, xenoliths of the Britt granodiorite and the deformed supracrustal rocks occur throughout the Shannon Lake granite. Geochronology on the intrusive units for the Giants Range Batholith yield ages of 2681-2685 ±4 Ma for the Britt Granodiorite and 2674±5 Ma for the Shannon Lake granite (Boerboom and Zartman, 1993). Based on geochronology and whole-rock geochemistry, the Shannon Lake granite is interpreted as S-type granite derived through crustal anatexis of sedimentary rocks, however a representative source material has not been identified (Boerboom and Zartman, 1993).

Garnet-Muscovite granites of the Pontiac subprovince and Lacorne Block of the Abitibi greenstone belt

The Pontiac subprovince is a metasedimentary-dominated terrane separated from the Abitibi greenstone belt to the north by the Kirkland Lake-Cadillac fault (Fig. A1). The Lacorne block is a fault-bounded block within the Abitibi greenstone belt which is similar to the Pontiac subprovince in that both contain high grade metamorphic rocks and migmatites, relatively mature sediments with detrital zircons older than 2.8 Ga, and late tectonic (~2645 Ma) S-type granites with Mo, Li, Be, and U pegmatites (Card, 1990; Dawson, 1966; Feng and Kerrich, 1992a; 1991; 1990; Gariépy et al., n.d.; Ludden et al., 1986). The "garnet-muscovite granites" (GMG series) of the Pontiac subprovince and the Lacorne block have been interpreted as having formed during intracrustal melting of Pontiac metasediments during continent-arc collision involving the thrusting of Pontiac subprovince under the Abitibi greenstone belt southern volcanic zone (Feng and Kerrich, 1992b). Pontiac metasediments can be divided into two subtypes: (1) turbidites with mafic and felsic volcanic rocks as their protoliths; and (2) mature turbiditic sediments derived from evolved crustal rocks with older ages (~3.1 Ga) (Feng *et al.*, 1993). The latter have been suggested to be the source rocks for the GMG series based on the intimate filed association of the GMG series plutons and migmatites with Pontiac metasediments (Feng and Kerrich, 1992b). Detrital zircon U-Pb ages from the metasediments and ages of cross-cutting plutons bracket the deposition of greywacke in the Pontiac subprovince to 2685 ± 3 Ma into a what was likely a foreland basin (Davis, 2002). Although we did not analyze any samples from the GMG series, we use previously published data for 15 samples from the Preissac, Lacorne, Lamotte, and Moly Hills plutons of the Lacorne Block (Feng, 1992; Feng and Kerrich, 1992b; Mulja et al. 1995a,b).

Mt. Owen batholith, Teton Range, Wyoming craton

The Mt. Owen batholith is located in the Teton Range of the Sweetwater subprovince of the Wyoming craton (Fig. 1), which is characterized by granites and gneisses recording late Archean (2.7 to 2.5 Ga) deformation and magmatism (Chamberlain *et al.*, 2003). Archean rocks in the Teton Range comprise several para- to orthogneisses deposited/emplaced before deformation and two later non-deformed plutonic units, the Rendezvous hornblende gabbro and the Mount Owen batholith. The Mount Owen batholith is a muscovite-bearing (and locally garnet-bearing) leucogranite that varies from fine-grained to pegmatitic (Frost *et al.*, 2006; 2018). U-Pb zircon geochronology indicates that the Mount Owen batholith crystallized at 2547±3 Ma (Zartman, 1998). We analyzed one sample from the Mount Owen batholith (98-T1), of which the whole rock major and trace element geochemistry, as well as, Nd and Sr isotope ratios, have been previously characterized by Frost et al. (2006). The Mount Owen batholith is moderately to strongly peraluminous (ASI = 1.0-1.3), has trace element trends controlled by differentiation of plagioclase and zircon, and has high initial $^{87}Sr/^{86}Sr$ ratio values (0.77096) and negative epsilon Nd values (-0.9) similar to quartzo-feldspathic gneiss in the area (Frost *et al.,* 2018). These compositional features suggest that it formed from crustal melting of pelitic or psammitic metasedimentary rocks after deformation associated orogenesis in the Teton Range at ~2670-2680 Ma, however specific source rocks have not been identified (Frost *et al.*, 2006).

PROTEROZOIC LOCALITIES

Harney Peak granite, Black Hills, South Dakota

The Harney Peak granite is a zoned, peraluminous intrusion near the eastern limit of the Wyoming Province with associated pegmatites that has been dated at 1.72 Ga (Redden *et al.*, 1990) (Fig. 1 in manuscript). Marking the culminating magmatic event for the Trans-Hudson orogeny, it was emplaced during a regional metamorphic and deformational event characterized by sillimanite-grade, 0.3-0.4 GPa regional metamorphism of late Archean to early Proterozoic metasedimentary rocks (mostly quartz-muscovite and quartz-biotite garnet schists) exposed around and within the granite (Helms and Labotka, 1991; Redden *et al.*, 1985). The Harney Peak granite comprises a main central pluton with multiple satellite intrusions and isolated sills. The main central pluton is characterized by a core of biotite + muscovite granite and an outer zone of muscovite + tourmaline ± garnet granite. Biotite is the dominant ferromagnesian phase in the core, whereas tourmaline dominates the perimeter granite and satellite intrusions (Nabelek *et al.*, 1992a). These two minerals are observed to coexist in only a few samples.

Previous geochemical studies have demonstrated several important features about the Harney Peak granite. First, the inner biotite-bearing and outer tourmaline-bearing suites likely have distinct source rocks. This is based on differences in oxygen isotope ratios, Sr and Nd isotope ratios, and trace-element geochemistry: The biotite-bearing granites have on average lower $\delta^{18}O$ values (11.5±0.6‰, relative to VSMOW) as compared to the tourmaline-bearing granites (13.2±0.8‰), which is difficult to explain through magmatic differentiation, subsolidus interaction with external fluids, or assimilation, suggesting distinct sources (Nabelek *et al.*, 1992b). In addition, the biotite-bearing granites likely contain both Archean and Paleoproterozoic sediments in their source regions based on Sr and Nd isotope data, whereas the Sr and Nd isotope data for the tourmaline-bearing granites only require Paleoproterozoic sediments in their sources (Walker *et al.*, 1986). It has thus been suggested that the lower $\delta^{18}O$ biotite granites were generated from a mixed early Paleoproterozoic and late Archean metasedimentary source at ~5-6 kbar, >800ºC, and at water-undersaturated conditions (through dehydration melting of biotite, (Nabelek *et al.*, 1992a). The ascent of these melts through higher levels in the crust during the peak of regional metamorphism lead to smaller degree, lower pressure melts of muscovite-bearing metasediments resulting in the production of B-rich tourmaline-bearing granitic melts characteristic of the outer zone of the pluton (Nabelek et al., 1992a).

Hepburn intrusive suite, Wopmay orogen, Northwest Territories

The Wopmay orogen is a Paleoproterozoic (1.9 Ga) collisional belt located on the western edge of the Slave craton (Fig. 1 in manuscript) (Hoffman and Bowring, 1984). The eastern part of the Wopmay orogen comprises the Coronation supergroup (which preserves a west-dipping sedimentary prism with rift-fill, passive margin) and foredeep flysch/molasses sequences that accumulated within a back-arc basin (Hildebrand *et al.*, 1987; Lalonde, 1989). In the western part of the supergroup, these sedimentary units were thrust onto underlying Archean basement, translated eastward, and subsequently intruded and metamorphosed by the Hepburn intrusive suite during the Calderian orogeny (King, 1986), ~1885 Ma (Hoffman and Bowring, 1984). The Hepburn intrusive suite is composed of ~100 plutons with 2750 km^2 of exposure along two N-S trending belts (Lalonde, 1989). The plutons of the Hepburn intrusive suite vary continuously from gabbro to granite, but they are dominated by peraluminous monzogranites and syenogranites.

Field relationships, peraluminous geochemistry and mineralogy, and elevated $^{18}O/^{16}O$ whole rock ratios, suggest a strong role for crustal assimilation in the formation of the Hepburn intrusive suite (Lalonde, 1986). First, the oldest granitic plutons of this suite are mildly foliated and contain metasedimentary xenoliths and schlieren (Lalonde, 1986). These granites are characterized by peraluminous mineralogy including muscovite, garnet (likely xenocrystic), and porphyroblasts of sillimanite (Lalonde, 1986; Pattison *et al.*, 1982). In addition, Pb bulk rock isotope studies suggest that the sedimentary material incorporated in the magmas was Proterozoic and not Archean in age (Housh *et al.*, 1989) and no inherited Archean zircons have been observed (Bowring, 1984). In contrast, the presences gabbros in the Hepburn intrusive suite demonstrates that mantle-derived magmas were likely an important source of mass and heat to the intrusive complex. Lalonde (1989) argues that the mafic magmas likely formed during a back-arc rifting event. Metamorphic studies of the Coronation Supergroup sedimentary sequences (St Onge, 1987; St Onge and King, 1987) suggest that regional metamorphism in the area of the Hepburn Intrusive Suite began under low pressure (<0.3 GPa), high temperature (550ºC) conditions consistent with rifting, which later evolved to higher pressure (up to 0.8 GPa) and temperature (650ºC) regime due to subsequent crustal thickening during closure of the back arc basin. Thus, the Hepburn intrusive suite is suggested to have originated in a rifting back-arc environment which rapidly evolved into a collisional setting with an associated anatectic metamorphic event (Lalonde, 1989).

Southwestern United States, peraluminous granites (1400-1500 Ma)

The time period of 1600 to 1300 Ma in Laurentia was characterized by extensive magmatism resulting in an transcontinental belt of granites across the United States and Canada (Anderson and Bender, 1989; Anderson and Morrison, 2005). This magmatism has been classically considered to anorogenic, resulting from low degrees of partial melting of dominantly Paleoproterozoic or older crustal sources (Anderson and Bender, 1989; Anderson and Morrison, 2005; Creaser *et al.*, 1991; Rämö *et al.*, 2003). However, another group of studies has suggested that the magmatism is an in-board expression of continued orogenesis on the margin of Laurentia (Karlstrom *et al.*, 2001; Kirby *et al.*, 1995; Nyman and Karlstrom, 1997; Nyman *et al.*, 1994). Although most of these intrusions are metaluminous, biotite+titanite±hornblende granites belonging either to an ilmenite- or a magnetite-series (Anderson and Bender, 1989; Anderson and Morrison, 2005), a third group, and the ones included in this study, are ca. 1400-1500 Ma peraluminous, two-mica granites forming a distinct province from Colorado to central Arizona and New Mexico (Fig. 1) (Anderson and Cullers, 1999; Anderson and Thomas, 1985). In this study, we used previously published data from the Silver Plume and St. Vrain granites of Colorado (Anderson and Thomas, 1985) and the Ak Chin, Ruin, Sierra Estrella, and Oracle granites of Arizona (Anderson and Bender, 1989). The peraluminous granites have been divided into two petrographic groups: (1) Silver Plume-type granites (located in Colorado) are relatively anhydrous based on the occurrence of magmatic sillimanite and late crystallization of muscovite, biotite, and fluorite (Anderson and Thomas, 1985); and (2) Oracle-type granites (located in Arizona) were emplaced under more hydrous conditions demonstrated by the early crystallization of biotite and muscovite and commonly lack sillimanite and fluorite as an accessory phase (Anderson and Bender, 1989). Although both these types of granites are similar to S-type granite in orogenic belts in terms of their peraluminous nature and high whole rock $\delta^{18}O$ (10.2-11.6‰, (Anderson and Morrison, 1992), they retain geochemical characteristic similar to "within-plate" granites such as high U, Th, Nb, and Y (Anderson and Cullers, 1999; Anderson and Morrison, 2005).

Nd isotope studies on the peraluminous Oracle-type granites of Arizona concluded that they were derived from Proterozoic crust (Farmer and DePaolo, 1984; Nelson and DePaolo, 1985). Although specific source materials have not been identified, whole-rock major- and trace-element and O isotope compositions are consistent with melting a peraluminous, quartzofeldspathic sedimentary source. Peraluminous two-mica granites from Arizona have crystallization ages varying from 1440±20 Ma (U/Pb zircon) for the Oracle and Ruin granites to c. 1380 Ma (Rb/Sr whole rock) for the Sierra Estrella granite (see summary in Anderson and Bender, 1989).

The Silver Plume and St. Vrain batholiths of the Colorado Front Range intrude Paleoproterozoic paragneisses and schists of the Idaho Springs Formation (Anderson and Thomas, 1985; Gable and Sims, 1969; Tweto, 1979) and range in composition from two-mica monzogranite to syenogranite with primary sillimanite occurring in the more evolved lithologies (SiO_2 > ~70 wt.%). Although Sr isotope compositions of the granites suggest that the Idaho Springs Formation is not itself the source material, the granites were likely derived through crustal melting of a similar peraluminous quartzofeldspathic source at pressures of 0.7-1.0 GPa (Anderson and Thomas, 1985; DePaolo, 1981). Precise crystallization ages are not available for the Silver Plume and St. Vrain batholiths, however Rb-Sr whole rock and mineral isochrons suggest crystallization from 1420 to 1450±30 Ma (Peterman *et al.*, 1968).

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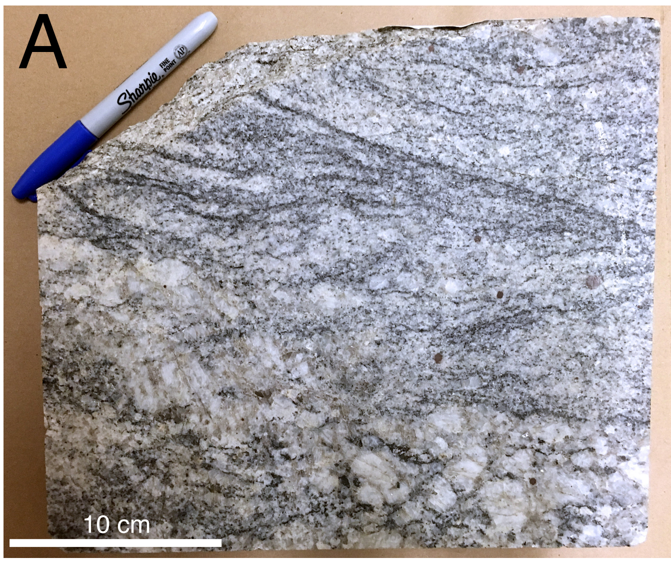
Sample Descriptions
Samples denoted in red are samples that were analyzed in this study for both petrography and mineral chemistry. Data for samples in black were compiled from the literature and were not examined directly. For these samples, petrographic descriptions were obtained from previous descriptions of the samples. Point counting was not undertaken for these samples, but all are granitic and many leucogranitic with <10% in modal abundance of mafic minerals.

ARCHEAN SAMPLES

GHOST LAKE BATHOLITH, ONTARIO, CANADA

E19-8: This sample is a medium-grained biotite-muscovite granite. Biotite is aligned in darker segregations forming a magmatic foliation. Coarser-grained segregations dominated by quartz and K-feldspar occur locally (Fig. A3), however the thin section analyzed in this study was cut from the homogeneous, finer-grained areas of the sample. Quartz occurs as anhedral grains with lobate boundaries or as inclusions in K-feldspar. Biotite often contains dark radiation damage halos (10-100 µms in diameter), forming around inclusions of radioactive accessory minerals such as monazite. Muscovite occurs as small laths, commonly interlocked with biotite. Accessory phases include zircon, monazite, and apatite.



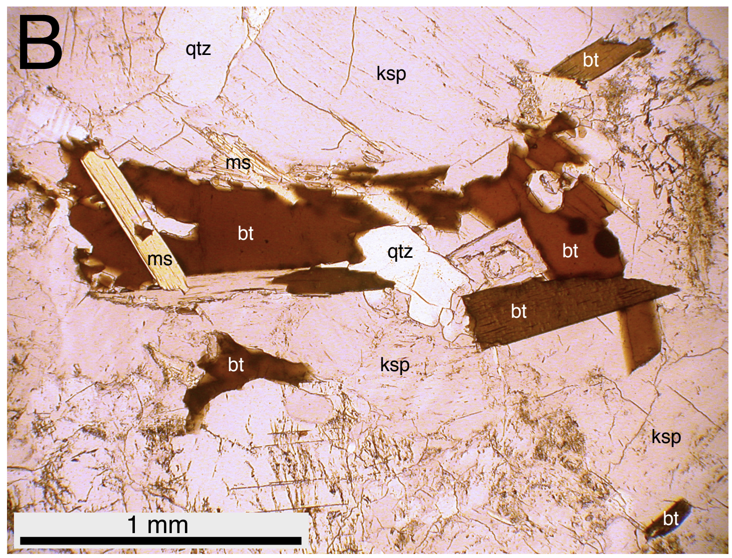


Figure A3: Sample E19-8 A) Photo of cut slab of sample. Thin section pictured in B was taken from the finer grained, foliated part of sample. Pegmatite facies of granites were avoided in this study. B) Photomicrograph showing typical interlocking textures of primary muscovite and biotite in this sample. Abbreviations: bt = biotite, ms = muscovite, ksp = K-feldspar, qtz = quartz.

SP-16-20a: This sample is a two-feldspar coarse-grained biotite-muscovite granite (Fig. A5). K-feldspar occurs as large (~ 1 cm) blocky crystals, commonly poikilitically enclosing biotite and K-feldspar. Quartz grains are anhedral and display undulose extinction. Biotite occurs as short blocky laths. Muscovite occurs as both primary laths and as a secondary phase along the boundaries of other grains and in quartz-muscovite symplectite intergrowths. Zircon is the primary accessory phase.

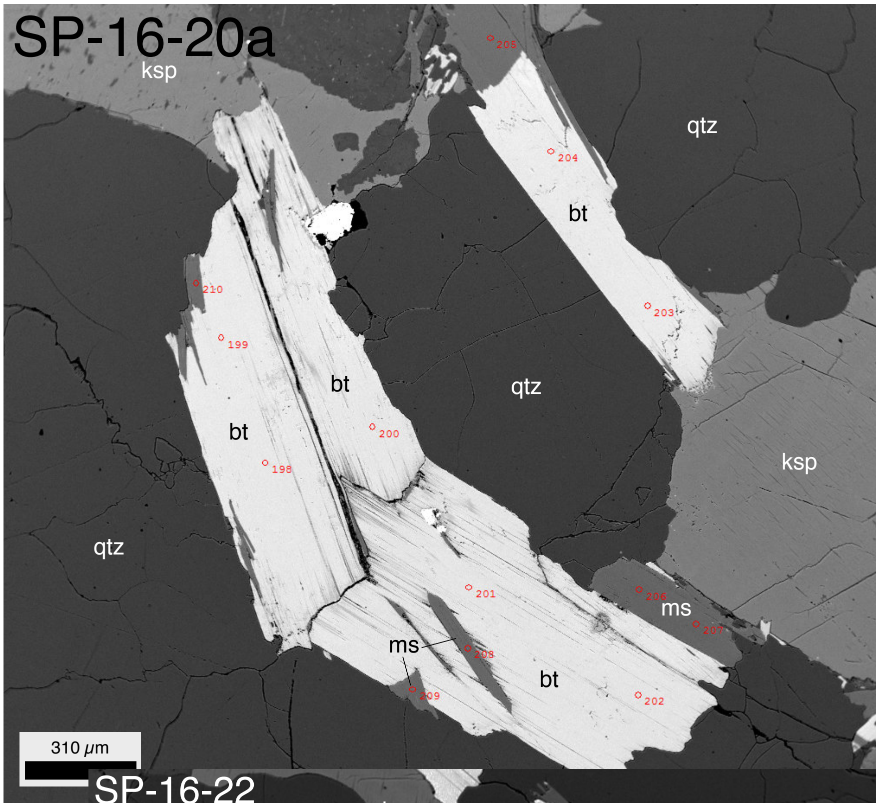


Figure A4*:* Sample SP-16-20a, BSE image demonstrating typical interlocking textures of biotite and muscovite. Bright inclusions in and along margins of biotite are zircons. (Red spots with numbers are locations of analyses taken within this photo.) Abbreviations as in Fig. A1. →

SP-16-22: This sample is a medium-grained hypidiomorphic granular biotite-muscovite granite. K-feldspar displays strong tartan twinning. Quartz occurs both as large (mm-scale) anhedral cyrstals and smaller 10's of μm scale rounded blebs included within other phases (Fig. A6) Muscovite occurs both as primary laths and secondary quartz+muscovite symplectites or anhedral growth rimming other phases. Biotite occurs as euhedral, early crystallizing laths that are "foxy" red under cross polarized light. Accessory phases include zircon and apatite. The crystallization sequence in this sample is biotite + plagioclase → muscovite + quartz → K-feldspar.

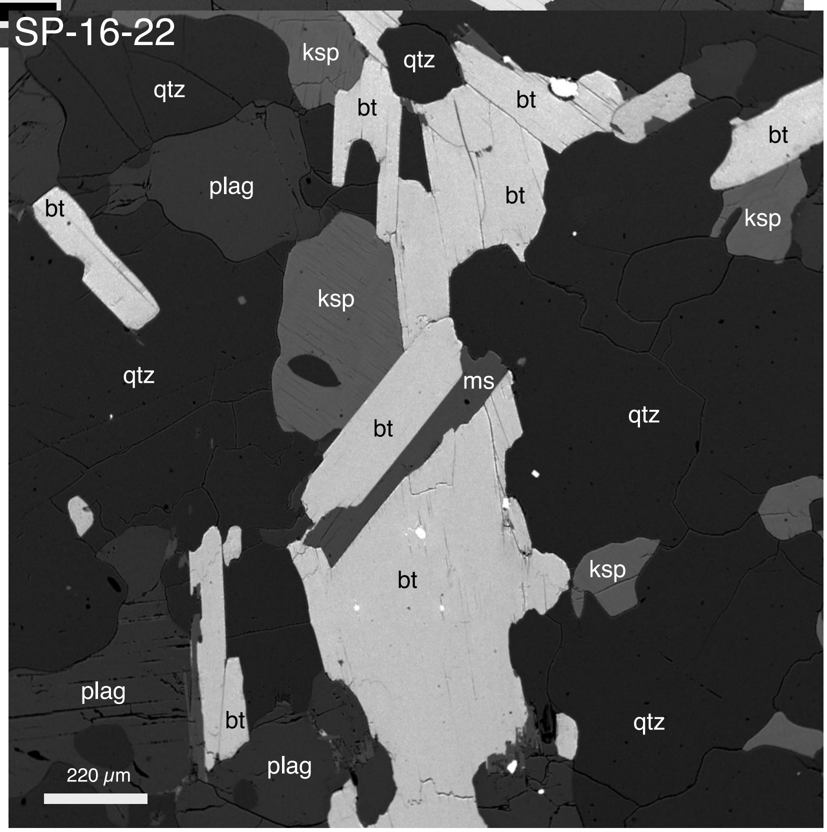
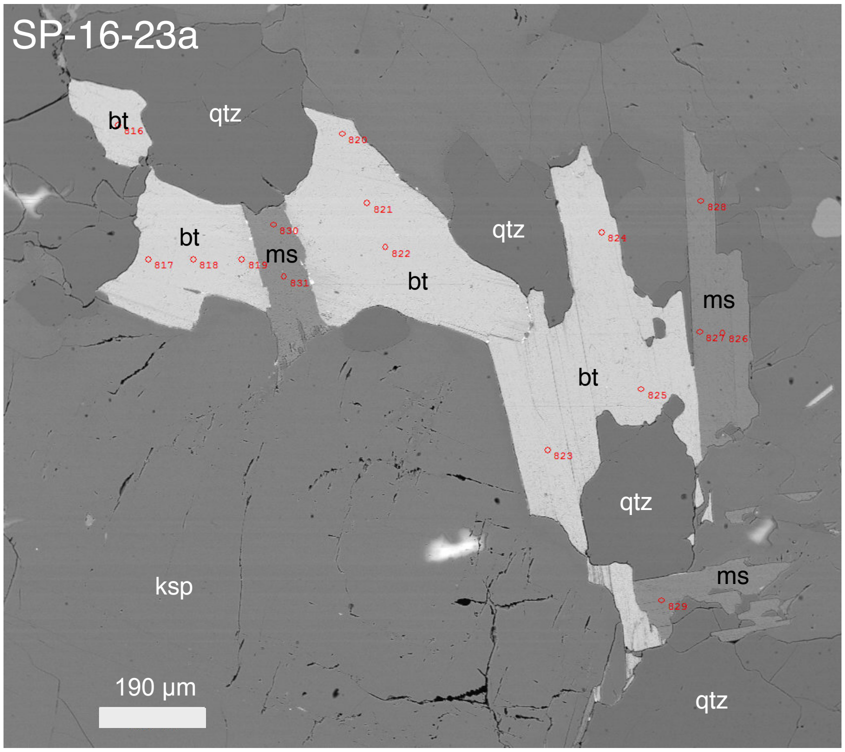


Figure A5*:* Sample SP-16-22, BSE image of characteristic textures observed in sample. Note occurrence of two feldspars. Bright inclusions in and along margins of major phases are zircon and apatite. Abbreviations: plag = plagioclase. →

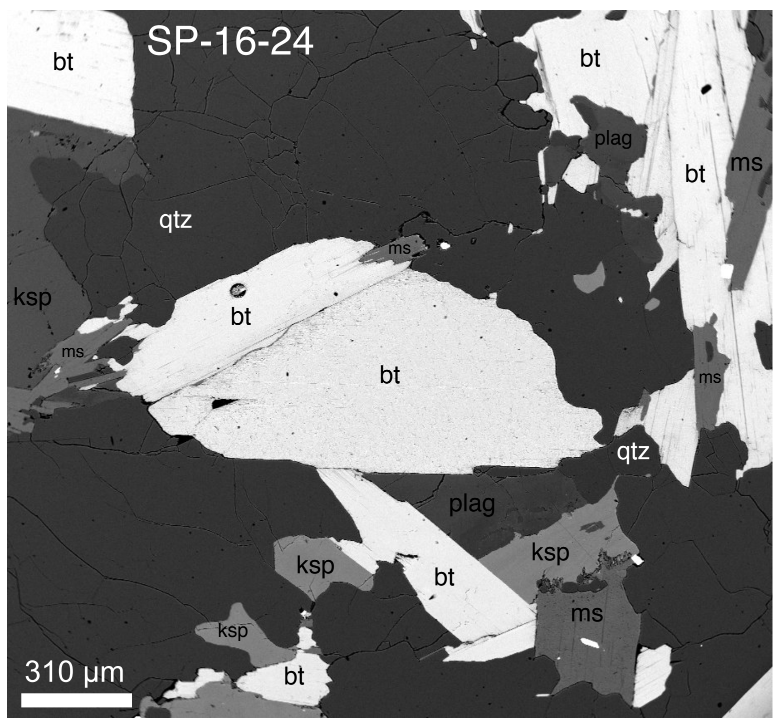
SP-16-23a: This sample is a medium-grained biotite-muscovite two-feldspar allotriomorphic granular granite (Fig. A7). Plagioclase appears to have crystallized late and contains abundant inclusions of K-feldspar, quartz, and muscovite. Small rounded quartz inclusions are commonly observed in both K-feldspar and plagioclase. Biotite occurs as anhedral, generally interstitial grains. Muscovite often is found as either elongate tabular crystals or in quartz-muscovite symplectites. Zircon is the primary accessory phase.



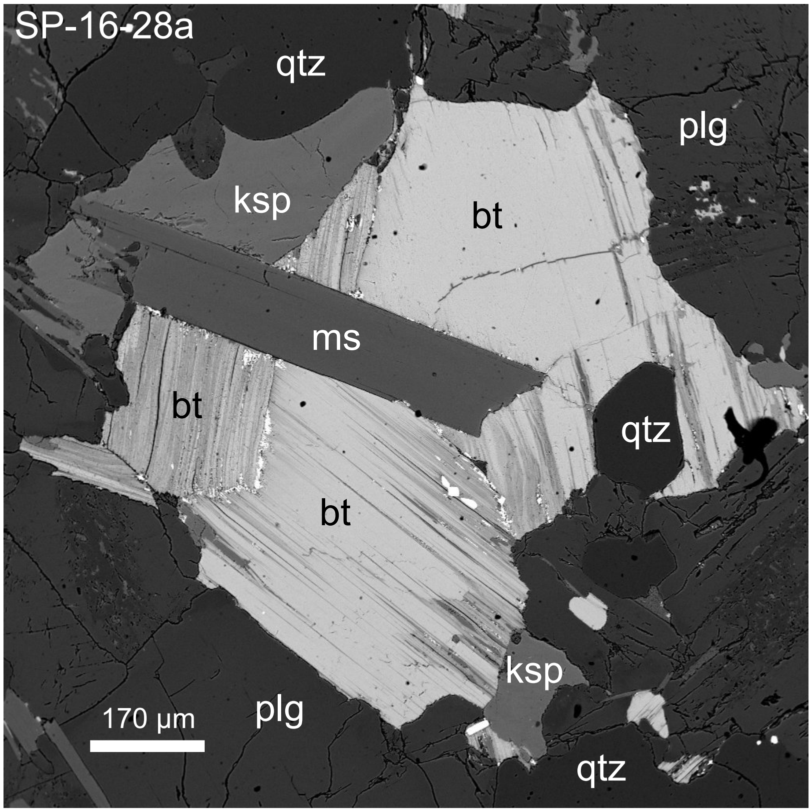
← **Figure A6***:* Sample SP-16-23, BSE image of characteristic textures observed in sample. Abbreviations as in previous figures. (Red spots with numbers are locations of analyses.)

SP-16-24: This sample is a medium-grained biotite-muscovite two-feldspar granite (Fig. A8). Crystals are generally anhedral except for biotite which often preserves its tabular shape. Muscovite occurs both as primary, subhedral laths and as secondary alteration along boundaries of other phases. Accessory phases include apatite and zircon. The crystallization sequence for this sample is plagioclase + biotite + muscovite → quartz → K-feldspar.

Figure A7*:* Sample SP-16-24, BSE image of characteristic textures observed in sample. Small (10's µms) bright grains are zircon. Abbreviations as in previous figures. →

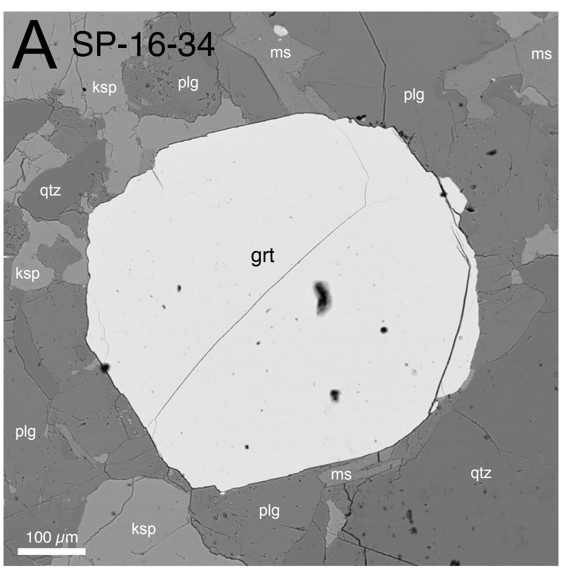


SP-16-28a: This sample is a medium-grained equigranular hypidiomorphic bt+ms granite (Fig. A9). Quartz occurs both as larger (mm-scale) rounded grains and as smaller included blebs within K-feldspar. Biotite is observed as stubby laths and commonly contains radiation halos. Biotite alteration to chlorite is observed locally. Muscovite occurs primarily as elongate laths and appears primary. Zircon and apatite occur as accessory phases.



← **Figure A8***:* Sample SP-16-28a, BSE image of characteristic textures observed in sample. Various degrees of alteration of biotite to chlorite are observed, but many grains preserve bright cores. Bright cores were targeted for chemical analysis. Alteration is associated with formation of oxides along margins of biotite. Abbreviations as in previous figures

SP-16-34: This sample is muscovite-garnet-tourmaline-biotite leucogranite dike in the host metasediments of the Ghost Lake Batholith (Fig. A10). Primary muscovite occurs as tabular crystals with irregular terminations. Secondary muscovite is present as ragged growths on grain boundaries and in quartz-muscovite symplectite intergrowths. Biotite is a minor phase but does occur as small (<1 mm) stubby laths. Plagioclase, K-feldspar, and quartz are all subhedral and rounded. Quartz display undulose extinction. Garnet is found in low abundances as small (100's µm in diameter) round, inclusion-free crystals. Zircon and apatite are the only accessory phase identified.



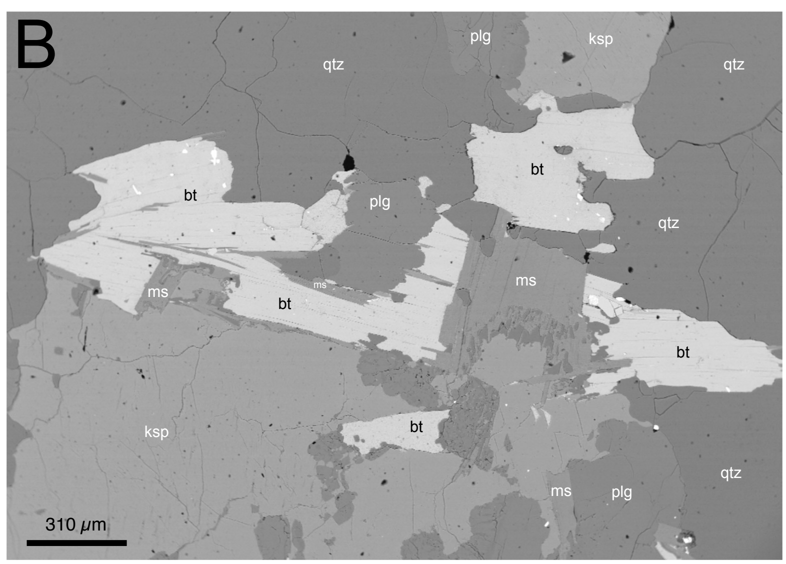


Figure A9: *Sample SP-16-34,* A) 500-600 µm diameter, inclusion-free garnet. B) Typical textures of biotite and muscovite. Note quartz-muscovite symplectic intergrowths on termination of muscovite crystals. Bright inclusions within biotite are predominantly zircon. Abbreviations as in previous figures.

STURGEON LAKE GRANITE, ONTARIO, CANADA

SP-16-48: This sample is a biotite-muscovite-garnet two-feldspar granite (Fig. A12). Plagioclase is heavily altered and retrograded. ~100 µm rounded quartz inclusions are abundant in K-feldspar. Biotite occurs as blocky tabular crystals. Incipient alteration to chlorite is observed in many biotite grains, however, cores of crystals generally appear unaltered. Garnet is observed as small (<1 mm), inclusion free anhedral crystals.

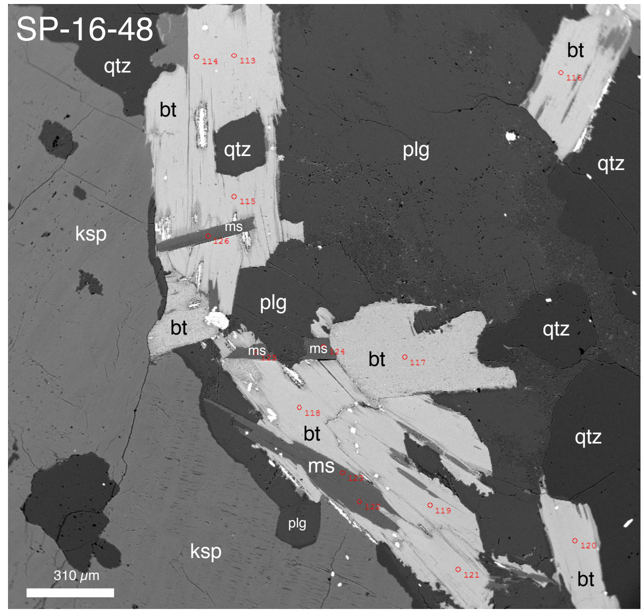


Figure A10: Sample SP-16-48, BSE photograph of interlocking biotite and muscovite. Biotite demonstrate incipient chlorite alteration, but generally preserves unaltered interiors. Bright phases are mostly zircon (as inclusions) and oxides as alteration products along margins on biotite. Abbreviations as previous figures. →

SP-16-52: This sample is a medium-grained allotriomorphic biotite-garnet±muscovite two-feldspar granite (Fig. A13). K-feldspar display pervasive tartan twinning. K-feldspar-quartz myrmmekitic intergrowths occur locally. Biotite occurs as subhedral tabular crystals interlocking with other phases. Rounded quartz inclusions are locally observed in both plagioclase and K-feldspar. Muscovite appears dominantly secondary occurring as ragged growths along grain boundaries of other phases. However, a few subhedral tabular muscovite crystals were observed and analyzed. Garnet crystals are generally highly anhedral and riddled with rounded 100's µm-scale quartz inclusions.

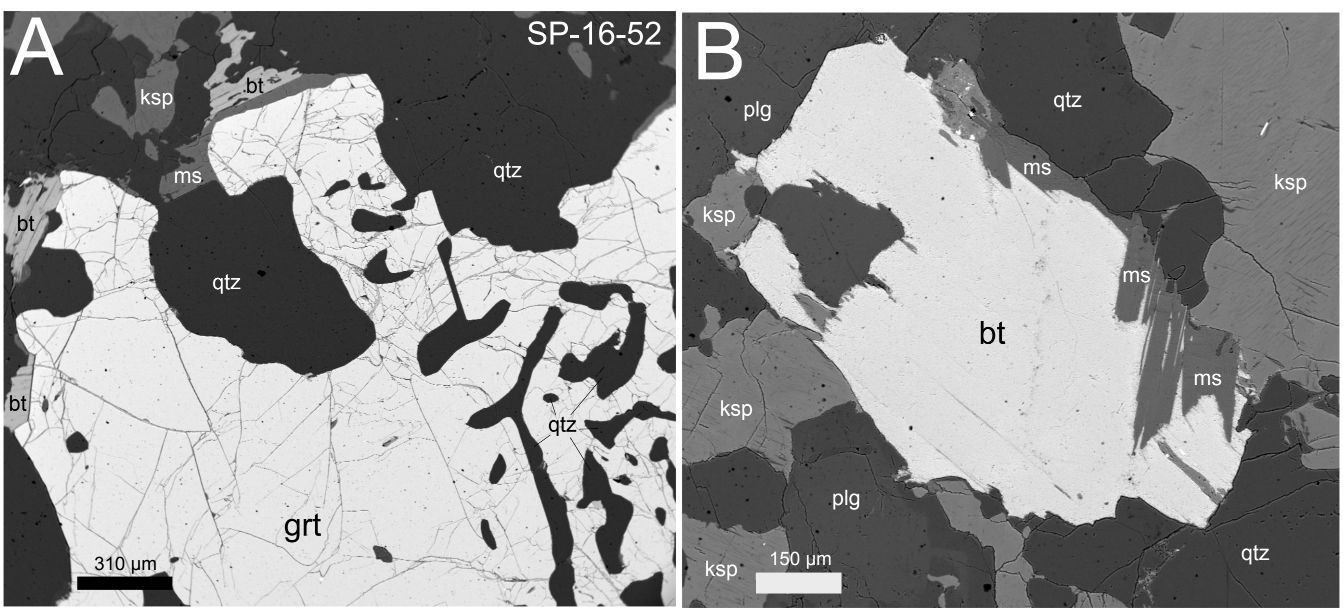


Figure A11: Sample SP-16-52, BSE photographs. A) cm-scale garnet with rounded quartz inclusions. Muscovite and biotite found along rim. B) Typical example of biotite and muscovite intimately intergrown with each other. Abbreviations as in previous figures.

SP-16-53: This sample is a biotite+muscovite medium-grained slightly foliated granite (Fig. A14). Plagioclase is heavily altered and retrogressed. Rounded quartz blebs (~100 µm in diameter) and blocky plagioclase crystals are commonly observed as inclusion in K-feldspar, suggesting that K-feldspar was a late crystallizing phase. Biotite often displays evidence for varying degrees of alteration to chlorite, however some grains preserve unaltered cores and were target for chemical analysis. Muscovite occurs as stubby tabular crystals with ragged terminations.

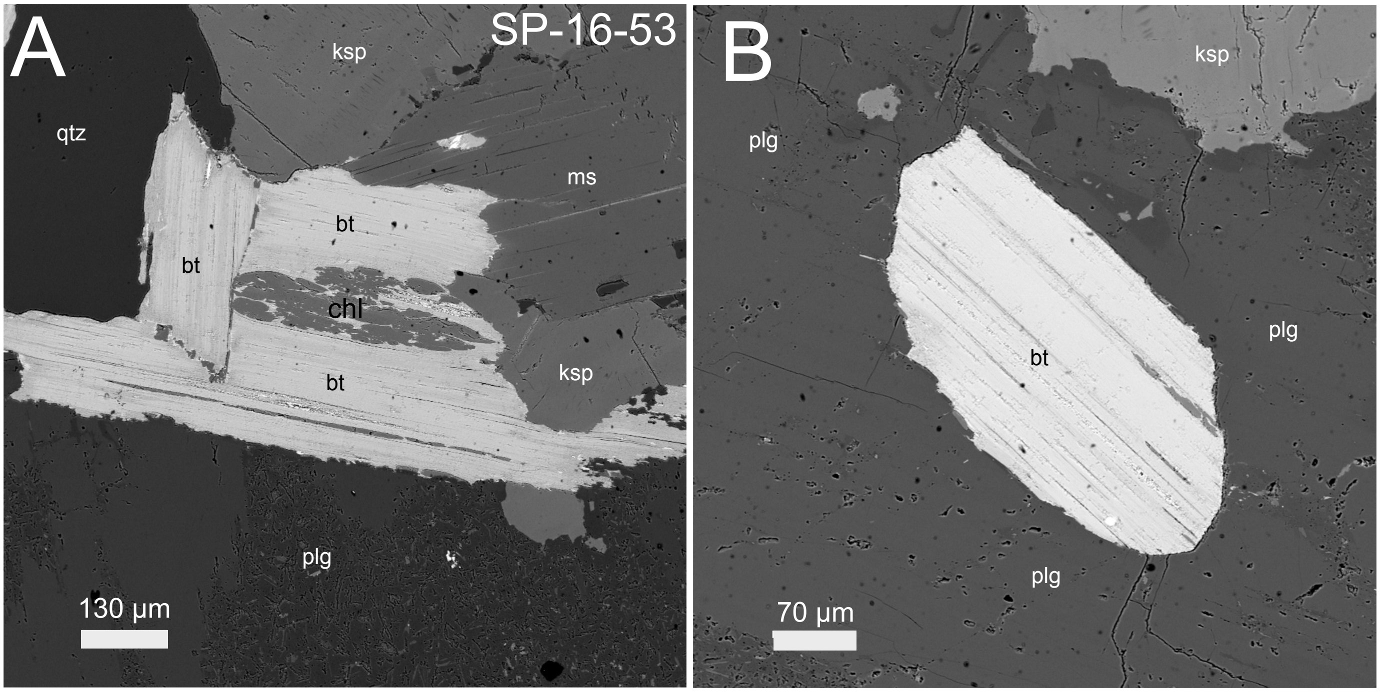


Figure A12*:* Sample SP-16-53, A) Example of pervasive biotite alteration to chlorite. Grains such as these were avoided during analysis. B) Relatively fresh biotite grain with only incipient alteration to chlorite along linear lamellae. Brightest areas of grains such as these were targeted for analysis. Note highly altered plagioclase in both A and B.

SHANNON LAKE GRANITE, MINNESOTA, USA

SP-16-1: This sample is a fine-grained, allotriomorphic, equigranular biotite+muscovite granite (Fig. A15). Plagioclase is heavily altered. Quartz occurs both as a ground mass phase and as small inclusions within plagioclase and K-feldspar. Muscovite and biotite occur as <500 mm tabular crystals interlocking in clusters. Biotite displays evidence for fairly extensive alteration to chlorite, however some cores appear fresh. Apatite (20-100 µm in diameter) and zircon are observed as accessory phases. The inferred crystallization sequence for this sample is quartz + plagioclase + biotite → K-feldspar + muscovite.

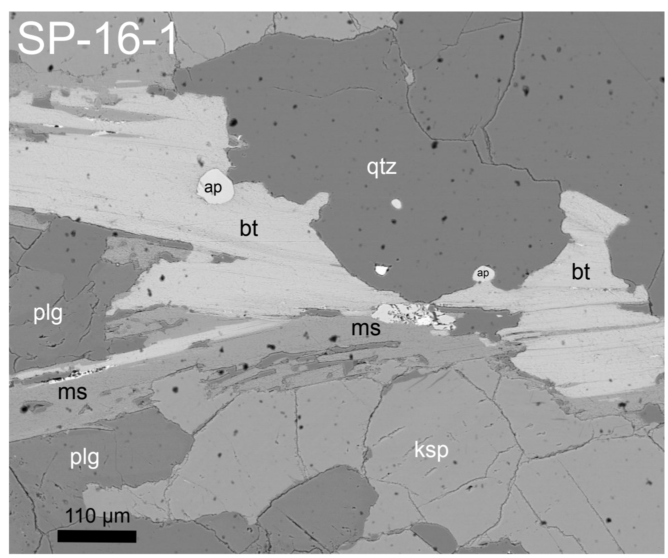
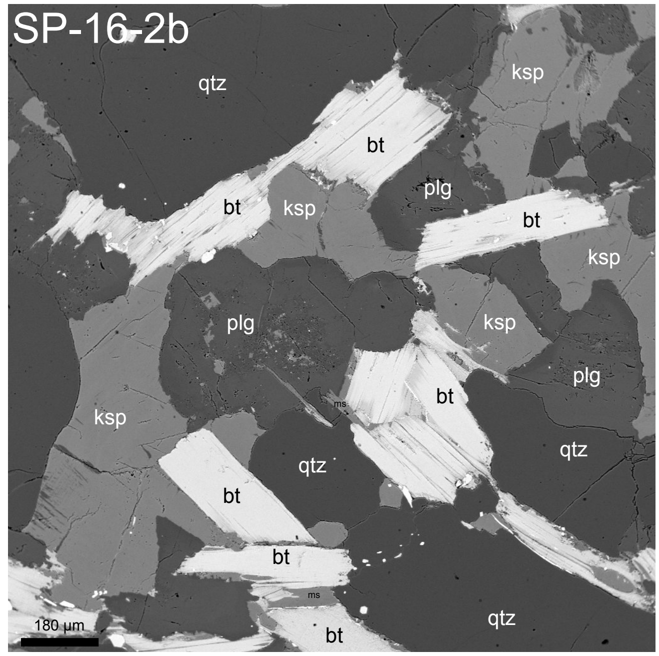


Figure A13*:* Sample SP-16-1, typical occurrence of biotite and muscovite laths. Note 10's µm round apatite grains. Ap = apatite. Other abbreviations as in previous figures.

SP-16-2b: This sample is a fine-grained biotite+muscovite granite (Fig. A16). Plagioclase is heavily altered and found both in the groundmass and as small inclusions within K-feldspar. Biotite occurs as lath-like crystals with irregular margins. Accessory phases include zircon and apatite. The crystallization sequence for this sample is plagioclase + biotite + muscovite → quartz + K-feldspar.

Figure A14: Sample SP-16-2b, typical occurrence of biotite in sample. Grains generally preserve bright interiors but do show alteration to chlorite along isolated lamellae. Note heavily altered plagioclase. Abbreviations as in previous figures. →



PONTIAC SUBPROVINCE AND LACORNE BLOCK, QUEBEC, CANADA

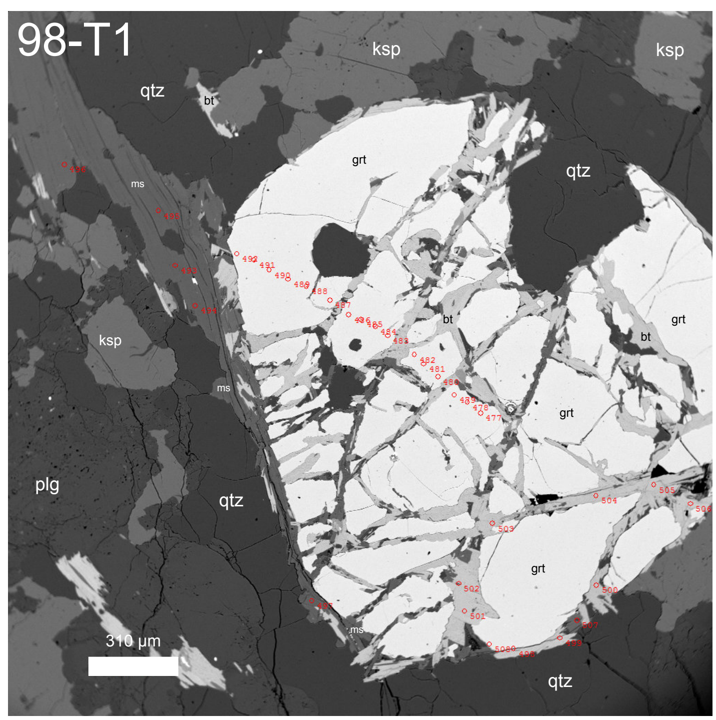
LC-8, LC-16-, LC-30: All of these samples contain magmatic muscovite (3 to 10%) and garnet (trace to 5%) (Feng, 1992; Feng and Kerrich, 1992). Other minerals include biotite (2-5%), quartz (~35%), K-feldspar (40-45%), plagioclase (5-20%). Average grain size is 1 cm.

903, 768, 797, 908, 616, 634, 652, 672, 692, 707, 26, 29: All of these samples are bt+ms±grt-bearing leucogranites (Mulja 1995; Mulja et al. 1995a,b). In addition, all the samples have similar proportions of interlocking quartz (25-35%), plagioclase (30-45%), and K-feldspar (25-45%). Plagioclase is the earliest mineral to have crystallized with plagioclase inclusions present in K-feldspar. Accessory minerals include Fe-Ti oxides, apatite, zircon, monazite, xenotime, and titanite.

MT. OWEN BATHOLITH, WYOMING, USA

98T1: This sample is a fine- to medium-grained biotite+muscovite+garnet two-feldspar granite (Fig. A16). Plagioclase is commonly heavily altered. Quartz occurs both as a groundmass phase and as small (~100 µm) rounded inclusions within K-feldspar and plagioclase. Muscovite and biotite occur as individual tabular laths or in interlocking clusters. Garnet is observed as round grains with quartz inclusions and a network of cracks lined with biotite, muscovite, and quartz. Zircon is the only accessory phase identified.

Figure A15: Sample 98-T1, 1-2 cm garnet with cracks filled by biotite and subordinate muscovite. In addition, the garnet contains inclusions of quartz. Muscovite and biotite also occur unassociated with garnet. Those grains were targeted for analyses used in this work. Red numbers and circles indicate analysis locations. →



PROTEROZOIC SAMPLES

HARNEY PEAK GRANITE

HP-21C: This sample is a medium-grained, hypidiomorphic granular biotite-muscovite granite (Fig. A18). Anhedral quartz displays undulose extinction and is often enclosed within K-feldspar. K-feldspar occurs as large (~10 mm) anhedral grains and encloses other phases (e.g. micas and quartz). Tartan twinning in K-feldspar is common. Plagioclase occurs as blocky, anhedral crystals occasionally with quartz myrmmekite overprinting polysynthetic twinning. Biotite and muscovite occur as elongate laths. Accessory phases include apatite (as small, rounded inclusions in K-feldspar), zircon, and rutile. The crystallization sequence in this sample based on textural relationships appear to be biotite + muscovite → quartz → plagioclase + K-feldspar.

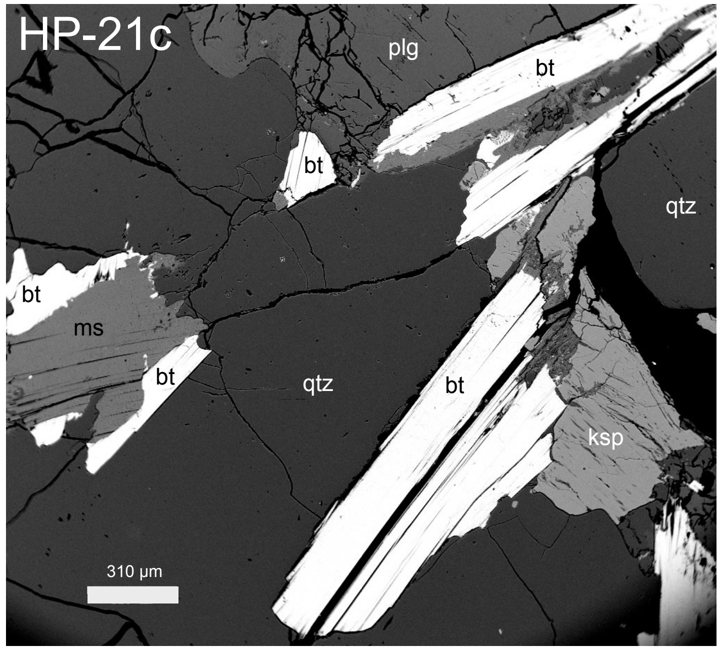


Figure A16*:* Sample HP-21c, example of large tabular grains of muscovite and biotite. Abbreviations as in previous figures. →

HP-32: This sample is a biotite+muscovite±garnet two-feldspar allotriomorphic granite granite (Fig. A19). Plagioclase often enclosed abundant inclusions of biotite and muscovite. Biotite occurs as elongate to stubby tabular crystals and often contains radiation halos. Muscovite is observed as short irregular grains. One small (1-2 mm) garnet was found in thin section.

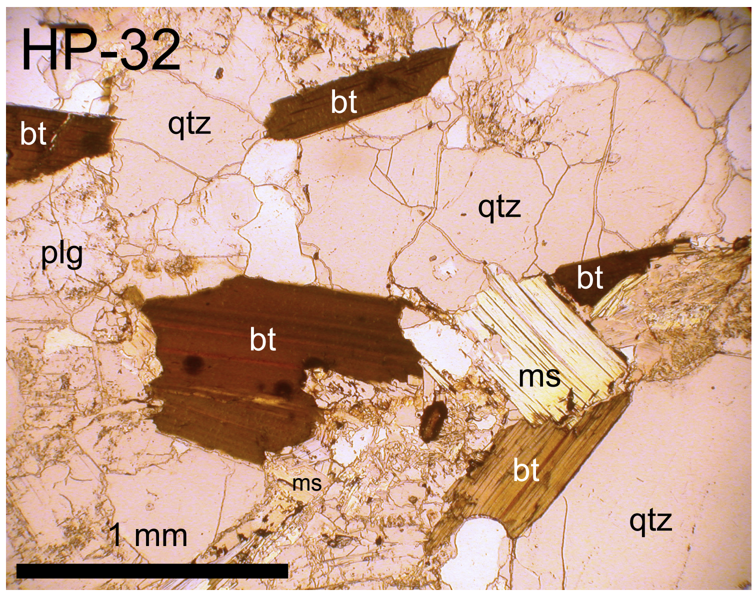


Figure A17*:* Sample HP-32, biotite+muscovite granite. Note radiation halos in large biotite grain (to left). →

HP-43A: This sample is a medium-grained, hypidiomorphic muscovite-garnet granite with minor biotite. Quartz occurs as anhedral, rounded grains with undulose extinction and is often found included in garnet or K-feldspar. K-feldspar and plagioclase generally form anhedral crystals and display tartan and polysynthetic twinning, respectively. Biotite occurs as small, rare laths. Muscovite occurs as blocky to elongate laths up to 5 mm in length. Garnet generally forms subhedral crystals and often contains inclusions of K-feldspar and quartz. Accessory phases include zircon, monazite, and rutile. Zircon and monazite are often found as inclusions within garnet. The crystallization sequence observed in this sample is quartz + K-feldspar + muscovite → garnet + plagioclase.

HP-44A: This sample is a medium- to coarse-grained garnet-muscovite granite with minor biotite. No garnet was observed in the thin section obtained for this sample, however is has been described in previous work as garnet-bearing (Nabelek et al. 1992). Quartz occurs as anhedral crystals with rounded margins, often as inclusions in K-feldspar. Biotite occurs as elongate laths, occasionally enclosed within K-feldspar. Muscovite occurs as anhedral elongate grains mostly on the boundaries of other minerals and sometimes displays a quartz-muscovite symplectitic intergrowth along margins of grains. Accessory phases include apatite, zircon, monazite, and rutile. The crystallization sequence for this sample is biotite + muscovite → quartz + K-feldspar + plagioclase. Garnet was not observed in thin section, therefore its order in the crystallization sequence is uncertain.

HP-6B, HP-7B, HP-26, HP-23A, HP-44A, HP-23A, HP-14A: Mineral and whole rock data for these samples was compiled from the literature (Nabelek et al. 1992) and therefore were not observed directly in thin section. However, Nabelek et al. 1992 provide an overview of their mineralogy. These samples belong to the low $\delta^{18}O$ series located in the core of the Harney Peak granite intrusion which are characterized by a mineralogy of quartz, sodic plagioclase (albite to oligoclase), orthoclase or microcline, biotite, and muscovite. Almandine-spessartine garnet is found in HP-23A, but is mostly absent in the low $\delta^{18}O$ series.

HEPBURN INTRUSVE SUITE, NORTHWEST TERRITORIES, CANADA

L14: This sample belong to the older intrusive granites of the Hepburn Intrusive Suite (Unit 4 in Lalonde, 1986) which consist of whit to dark grey biotite-muscovite monzogranite with lesser amounts of syenogranite and granodiorite. Widespread occurrence of metasedimentary enclaves is a characteristic feature of this unit. The unit is characterized by <6-15 cm euhedral white microcline megacrysts (20-45% in modal abundance) in a coarse-grained matrix of plagioclase (16-38%), smoky quartz (20-30%), minor K-feldspar, biotite (2-16%), and muscovite (trace-5%). The K-feldspar megacrysts often exhibit a rounded internal core surrounded by a rim containing abundant mineral inclusions. Accessory phases include garnet (trace – 3%), sillimanite (trace – 2%), zircon (trace – 1%), apatite (trace – 1%), allanite, and tourmaline. Opaque oxides are rare, but where present, dominated by ilmenite.

SILVER PLUME and ST. VRAIN GRANITES, COLORADO, USA

SP-6, SVL-3, SVL-4, SVL-5: Mineral and whole rock data for these samples was obtained through previously published data (Anderson & Thomas, 1985) and through personal communication with Lawford Anderson. SP-6 is a biotite-muscovite granite with plagioclase, quartz, large poikilitic K-feldspars, and accessory monazite, magnetite, and ilmenite. SVL-3 is a biotite-muscovite two-feldspar granite with moderate seriticizaiton of feldspars and accessory monazite, apatite, and magnetite. SVL-4 and SVL-5 are biotite+muscovite+sillimanite granites. SVL-4 contains accessory magnetite, ilmenite, hercynite-gahnite oxides, monazite, rutile, and molybdenite(?). SVL-5 contains magnetite, ilmenite, rutilte, zircon, and monazite.

AK-CHIN GRANITE, ARIZONA, USA

AMC-83-1, AMC-83-2: Mineral and whole rock data for these samples was obtained through previously published data (Anderson and Bender, 1989) and correspondence with Lawford Anderson. These samples are biotite-muscovite monzogranites with accessory ilmenite. Modal abundances are quartz (36-43%), alkali-feldspar (29-33%), plagioclase (23-24%), biotite (2%), zircon (0.1-0.4%), apatite (0.1%), muscovite (0.6%), epidote (0.2%), opaques (1%), and secondary chlorite (0.5-2%). Accessory phases include magnetite, less abundant ilmenite, monazite, allanite, apatite, xenotime, zircon, and rare fluorite (in AMC-83-1). Alkali-feldspar forms large poikolitic grains with inclusions of quartz and plagioclase, and near the margins, biotite, magnetite, and apatite.

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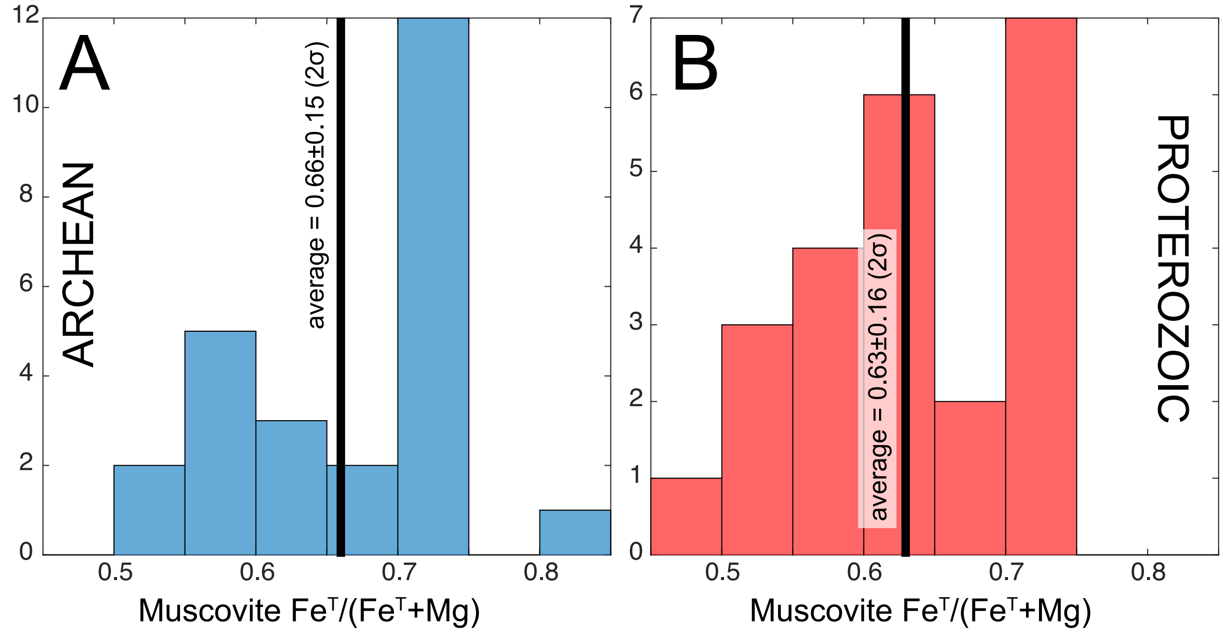

Figure A18: Histogram of muscovite $Fe^T/(Fe^T+Mg)$ values in A) Archean and B) Proterozoic samples.

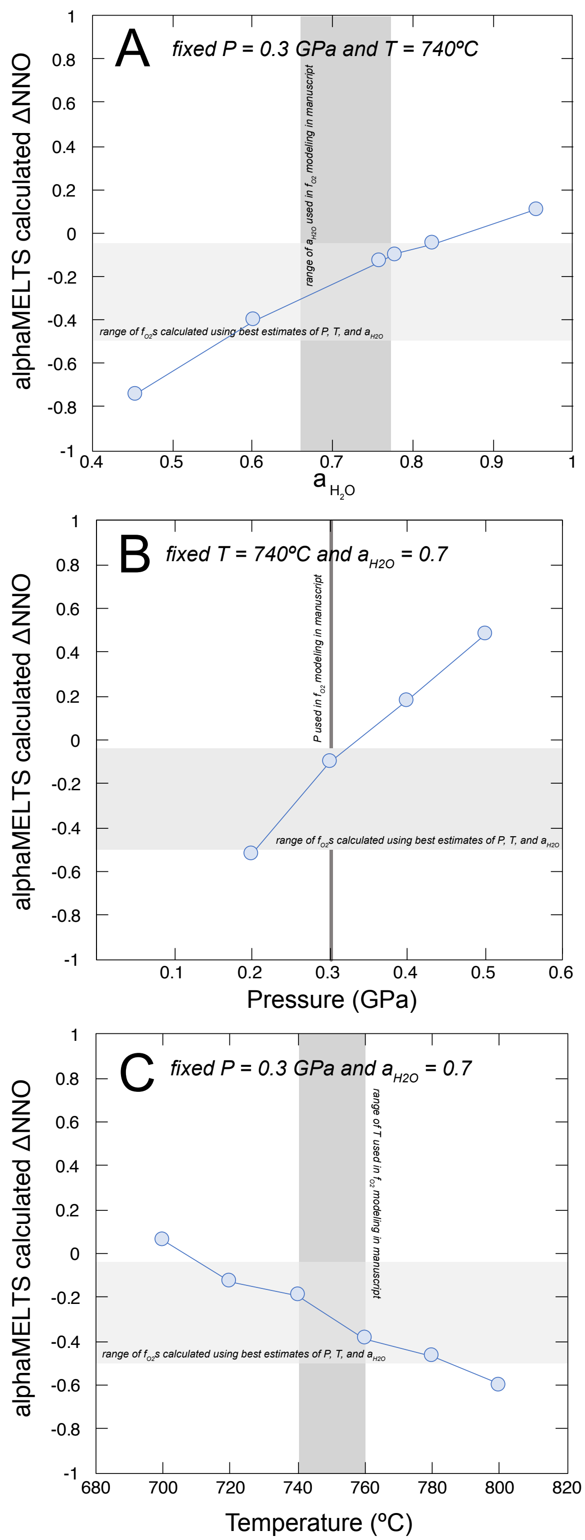

Figure A19: Sensitivity analysis results for oxygen fugacity alphaMELTS calculations for sample SP-3. A) Sensitivity to variations in a_{H2O} at fixed pressure and temperature. B) Sensitivity to variations in pressure at fixed temperature and a_{H2O}. C) Sensitivity to variations in temperature at fixed pressure and a_{H2O}.